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Title: High Fidelity MCNP Modeling of the Versatile Test Reactor

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High Fidelity MCNP Modeling of the Versatile Test Reactor

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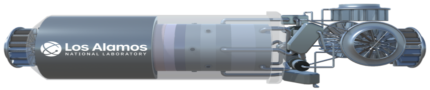
07/12/2021

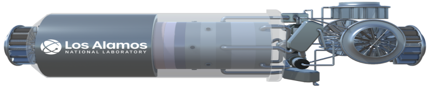
Unclassified

Outline



- What is the Versatile Test Reactor (VTR)?
- LANL VTR Responsibilities & Associated Collaborators
  - Neutronic and system confirmatory analyses
    - Note: System analyses not presented due to time constraints
  - Extended Length Test Assembly – Cartridge Lead (ELTA-CL) design
- MCNP Neutronic Analyses Methodology, Results, & Conclusions
- ELTA-CL Purpose & Design Process
- Effects of Cartridge on VTR Core Baseline

What is the VTR?



- The VTR is a sodium fast reactor (SFR) providing a very high fast flux irradiation capability
  - Ternary metal fuel (U-Pu-Zr) fuel rod, liquid sodium coolant
  - Numerous experimental locations within the core
- Why the VTR?
  - New materials and reactor concept testbed
  - VTR is intended to shorten the development and approval horizon for materials

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LANL Responsibilities for the VTR:

- Neutronic and system supporting design analyses
  - NEN-5 VTR confirmatory analyses using independent methods
    - The system response analyses are impressive, but not included here
- ELTA-CL (lead based experimental cartridge) design

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Westinghouse

THE UNIVERSITY OF NEW MEXICO

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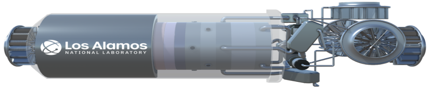
NEN-5 VTR Responsibilities – Neutronic Supporting Design Analyses



- VTR design (right) has primarily been conducted at ANL
- Radial view of the VTR layout
  - U-Pu-Zr fuel assemblies
    - 217 fuel rods per assembly
  - Control rod assemblies
  - Safety rod assemblies
  - Experiment assemblies
  - Reflector assemblies
  - Shield assemblies

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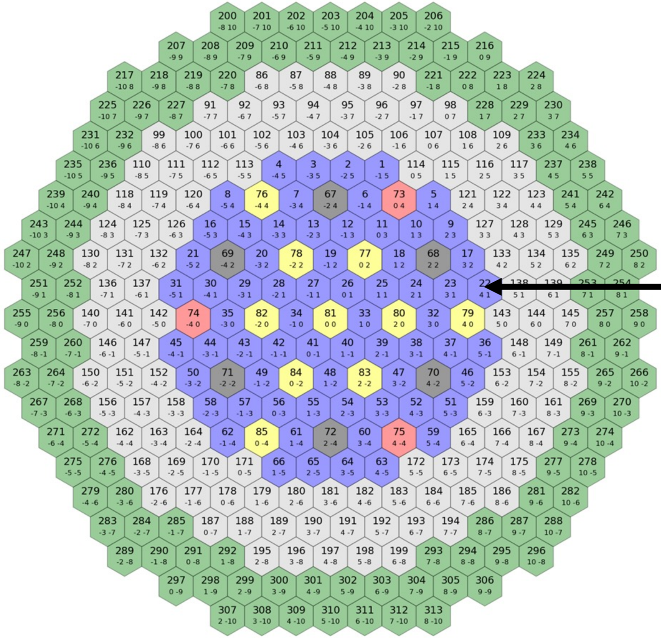
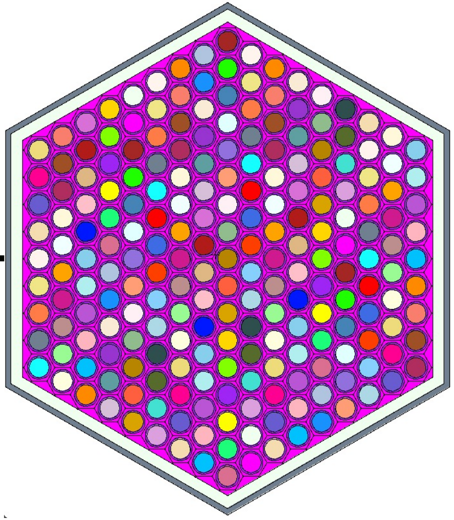
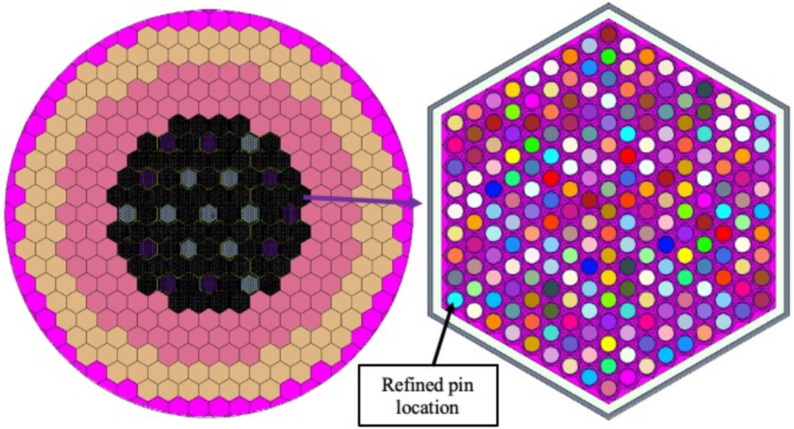
Core Map with hexagonal coordinates

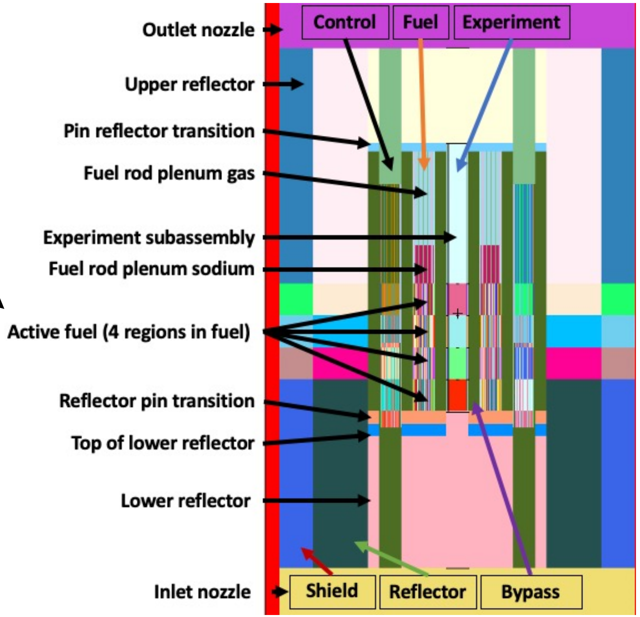




NEN-5 VTR Responsibilities – Neutronic Supporting Design Analyses

- MCNP model axial fidelity
  - Highly detailed in the active core
  - 4 axial regions in the active fuel
    - One refined fuel pin per assembly
  - Characterize:
    - Reactivity and kinetic parameters
    - Neutron flux & power
    - Photon flux & power
    - Control rod worth
    - Safety rod worth





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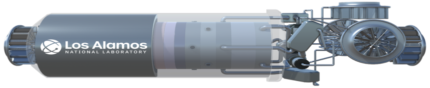
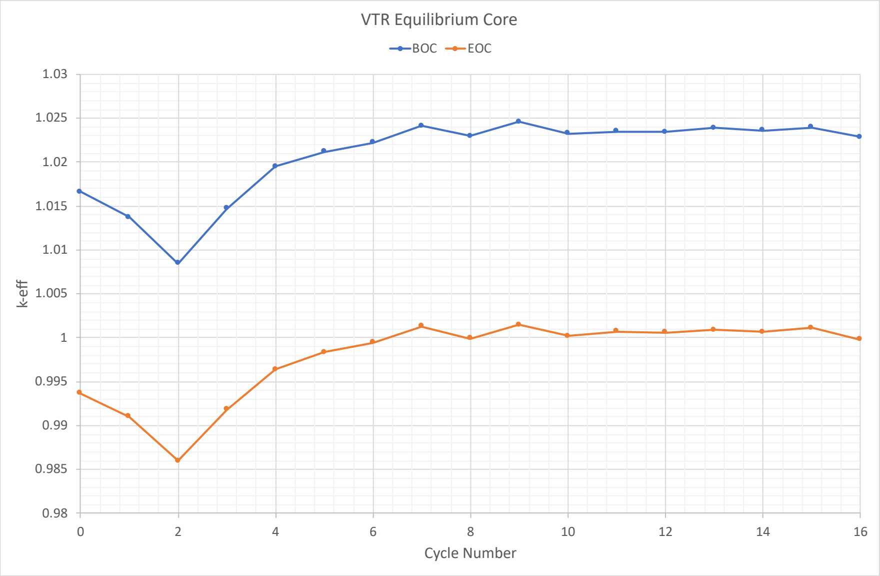
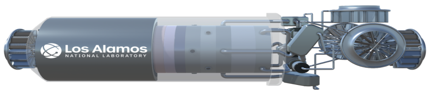
NEN-5 VTR Responsibilities – Neutronic Supporting Design Analyses, Equilibrium Core Analysis



- Equilibrium core, what is it?
  - ~60,000 depletion zones
  - Equilibrium essentially achieved at cycle 10
- High-fidelity MCNP model allows in-depth physics analysis
- How to calculate this?
  - Initially tried MATMOD or SWAPB
  - Difficulties with both
  - Eventually used inherent burnup coupled with manual material replacement via Python



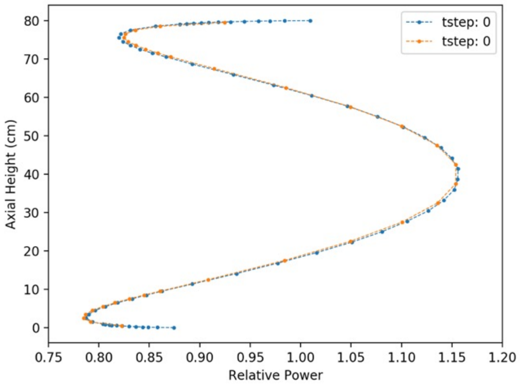

NEN-5 VTR Responsibilities – Neutronic Supporting Design Analyses

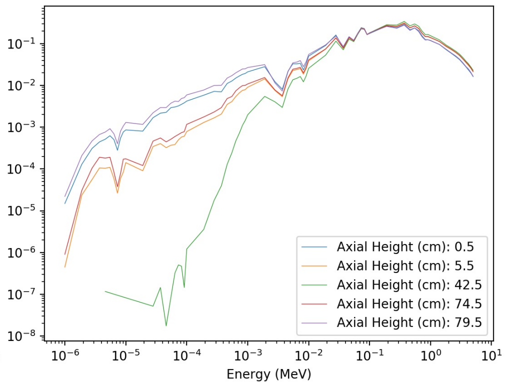


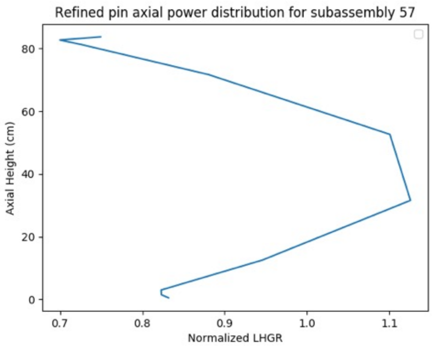
- High-fidelity MCNP model benefit
  - Pin-cell model versus whole core
  - Puzzling (unexpected) power peaking
  - Cause and implications?

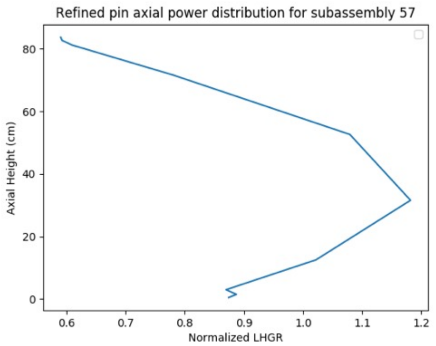
- New physical understanding garnered!
  - Cause: Slowing of fast neutrons towards the top of the rod (middle)
  - In reactor occurrence: Yes, but only sometimes (bottom)

- Particular importance for fuel failure mechanisms



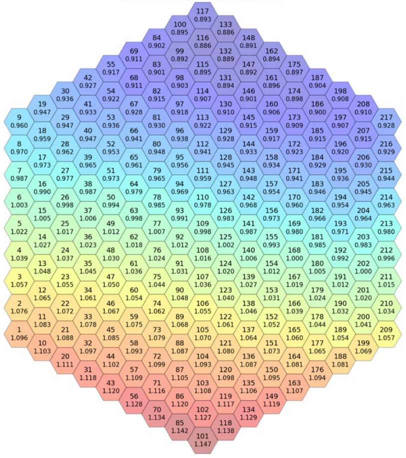


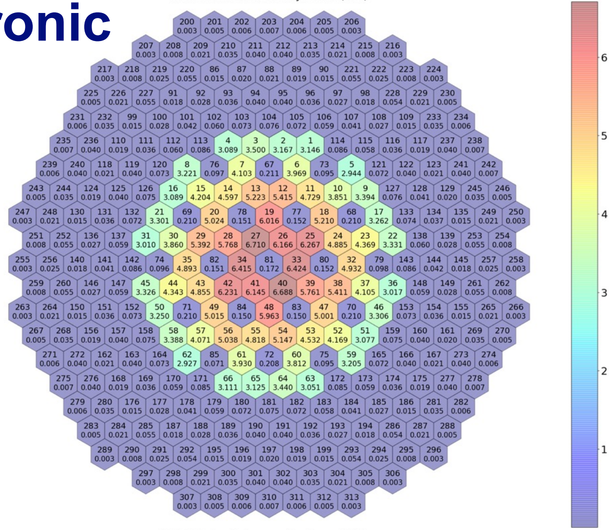


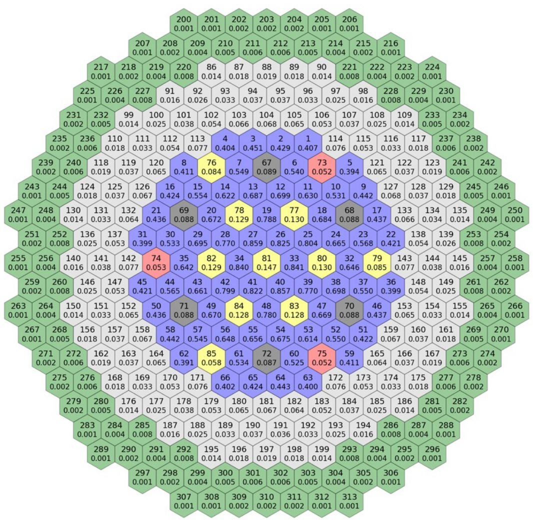


NEN-5 VTR Responsibilities – Neutronic Supporting Design Analyses

- Power distributions
  - Total power, neutron and photon contributions
  - Integral pin power peaking
    - Thermal limits implications
- Flux distributions
  - Neutrons and photons
  - Flux values at each location proved invaluable during ELTA-CL design iterations
- Further design analyses
  - Cartridge implications







Our work confirms the general design of the VTR core and highlights areas of increased importance

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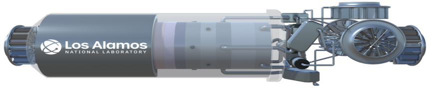
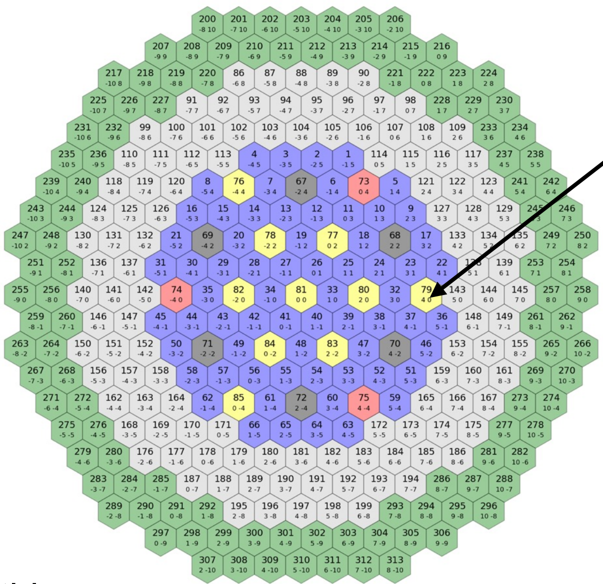
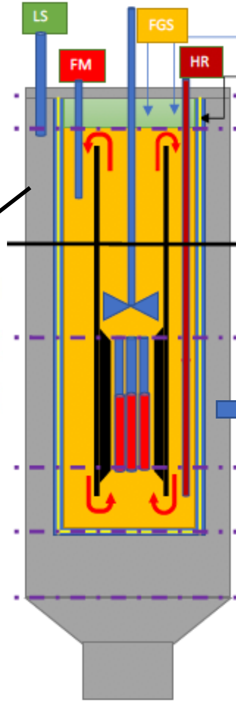
ELTA-CL Design Process – Purpose and Requirements



- What is the ELTA-CL?
- ELTA-CL purpose
  - Westinghouse reactor concept
- Desired information
  - Irradiated structural material erosion/corrosion
  - Fuel performance behavior under expected irradiated conditions
  - Irradiated material characteristics (irradiation growth, swelling, embrittlement)
- Requirements include
  - Target fuel linear heat generation rate (LHGR)
  - Bounding fast flux
  - Peak coolant temperature and velocity conditions & many more!
- The ELTA-CL design process aims to fulfill all requirements within the VTR core environment with no interference on the VTR core operation





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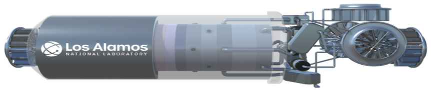
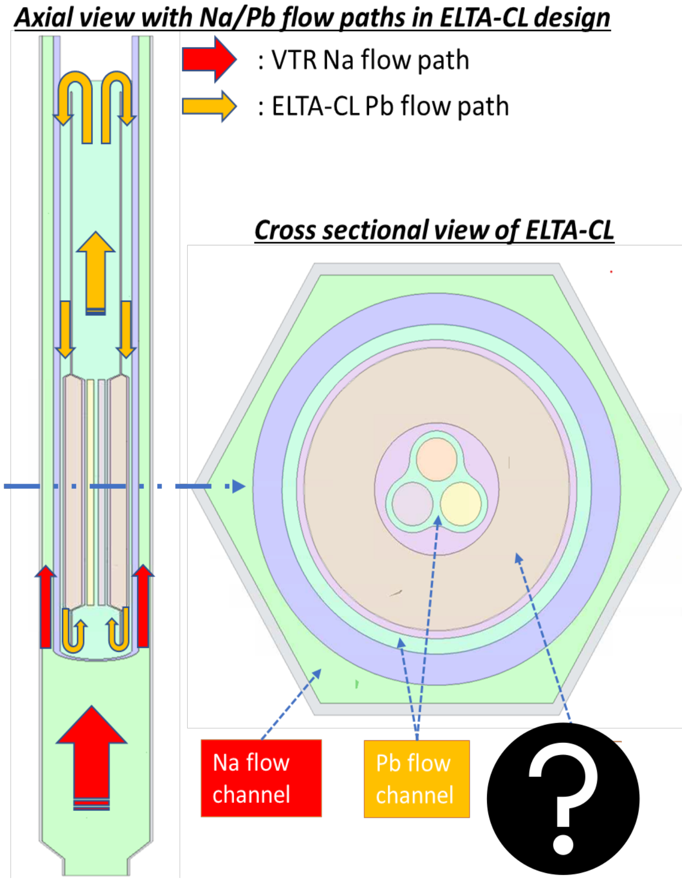
ELTA-CL Design Process



- Key design features:
  - Fueled rods (fissile) in the cartridge
  - Lead coolant flowing within the cartridge
  - VTR sodium heat sink
- Self-contained flow loop and heat generation
  - Multiple barriers
- The cartridge aims to satisfy regulatory (NRC) rigor
  - Generate experimental data
  - Validate models
  - Domains of safe operation
- What's the "?"



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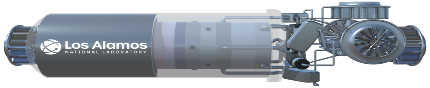
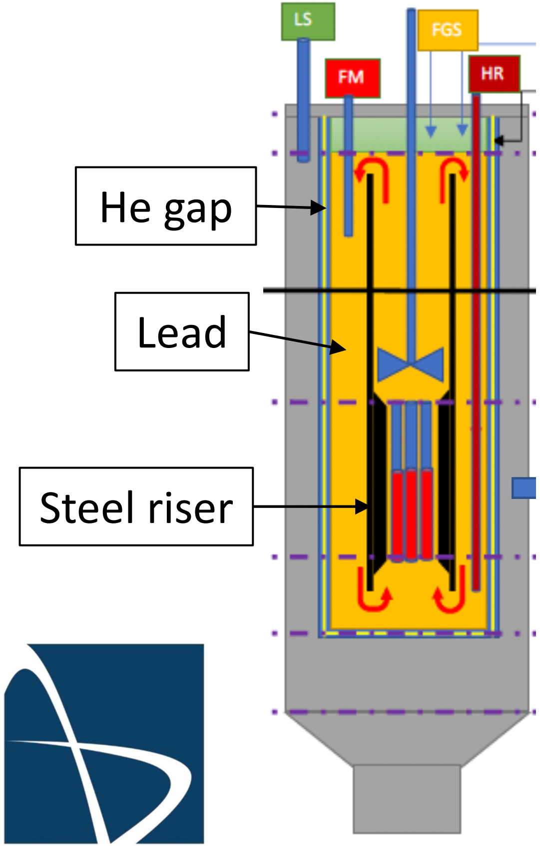
ELTA-CL Design Process – Baseline Design



- ELTA-CL baseline design
  - Thin He gap
  - Large lead volume
  - Solid steel riser
  - Preliminary calculations looked good
- Features included
  - He gap serving as the filler between safety barriers preventing lead leakage into the sodium core coolant
  - Simple design
- Problem: Unexpectedly high gamma heating
  - Must answer:
    - How high?
    - How to mitigate?



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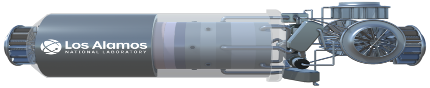


ELTA-CL Design Process – Baseline Design

- Utilize the high-fidelity MCNP model
- Model the ELTA-CL at internal and peripheral locations
- Gamma heating
  - 75-80% of heat deposition irrespective of position
  - Magnitude of heat deposition is position dependent
- Cartridge heating values are excessively high
  - Design modifications are a must

MCNP simulations of the VTR core highlighted that we needed to make significant design changes to accommodate the photon environment

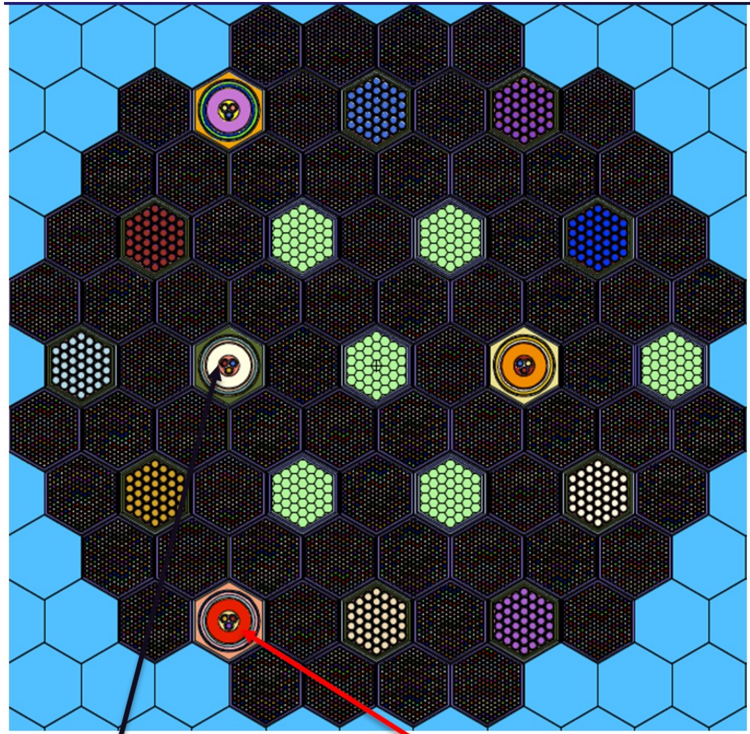
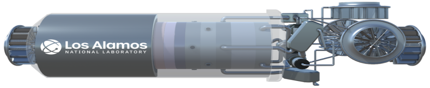


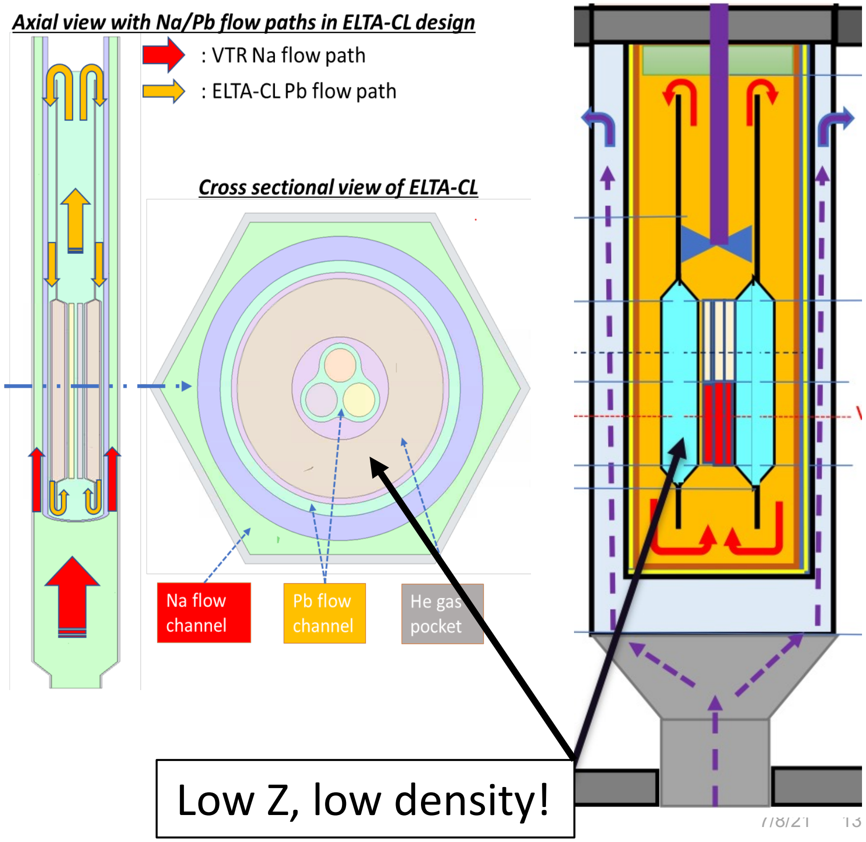
Figure 2 Experimental cartridge radial geometry

Internal (82) vs **Peripheral (85)**

ELTA-CL Design Process – Modified Design



- ? Revisited!
- Must lower lead temperature by:
  - Increasing heat transfer
  - Lowering heat (photon) deposition
- He safety gap changes
- Riser design modifications
  - Convective heat transfer
  - Expand the riser in the active core region
  - Lower high Z atom density, lower photon heating



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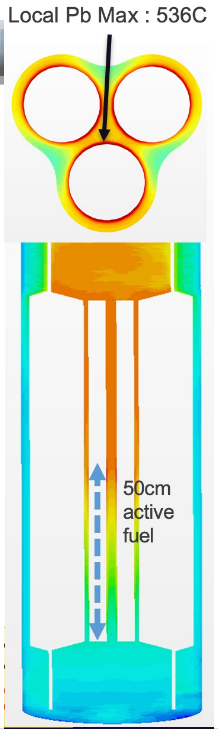
ELTA-CL Design Process – Modified Design



- The modified design sufficiently reduced photon heating
  - Only in the peripheral position
  - Determination: internal position has too high of a photon flux for a heavy metal cartridge
- Preliminary thermal calculations were simplified 1-D
  - Higher fidelity thermal modeling needed, thus CFD
- Simulate temperature response in 3-D
  - Determine radial temperature profile, compare to 1-D
  - The max CFD temperature ~20 C higher
- High fidelity multi-physics simulations informed that the local max temperature is above the design target
  - More design work needed

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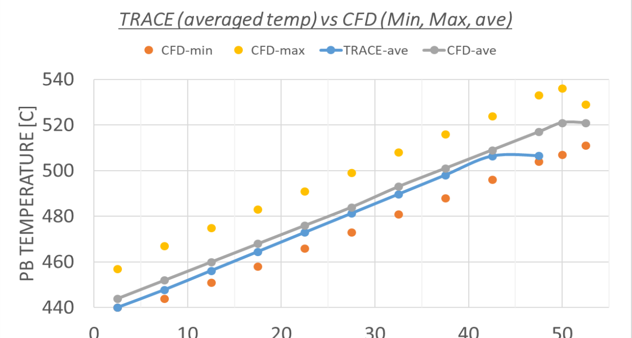

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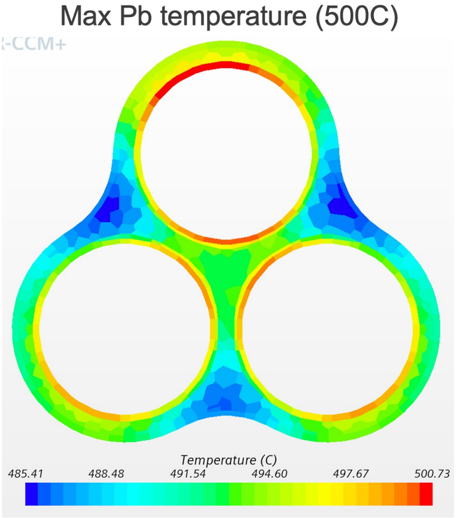
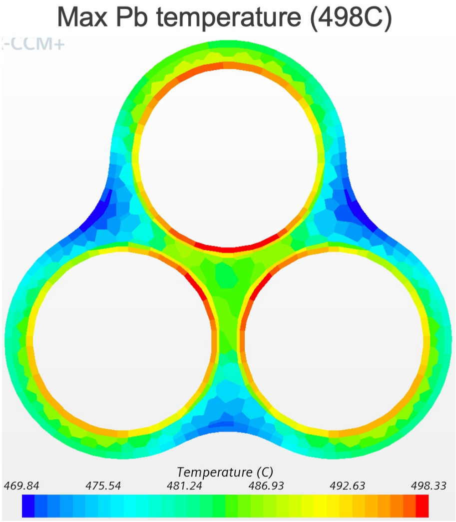
ELTA-CL Design Process – "More" Modified Design

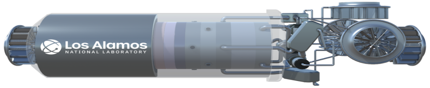
- Design changes "to date"
  - Adjust safety barrier fill, riser design, peripheral location
  - Still above design target by ~30ºC
- Next step, iterate on CFD simulations
  - Increase sodium flow rate (minimally effective)
  - Investigate axial enrichment variation in the fuel (top)
  - Increase "He pocket" within manufacturable tolerances (bottom)
- Successfully reduced max clad temperature to design target

Utilizing combined MCNP+CFD simulations, two viable design options have been determined

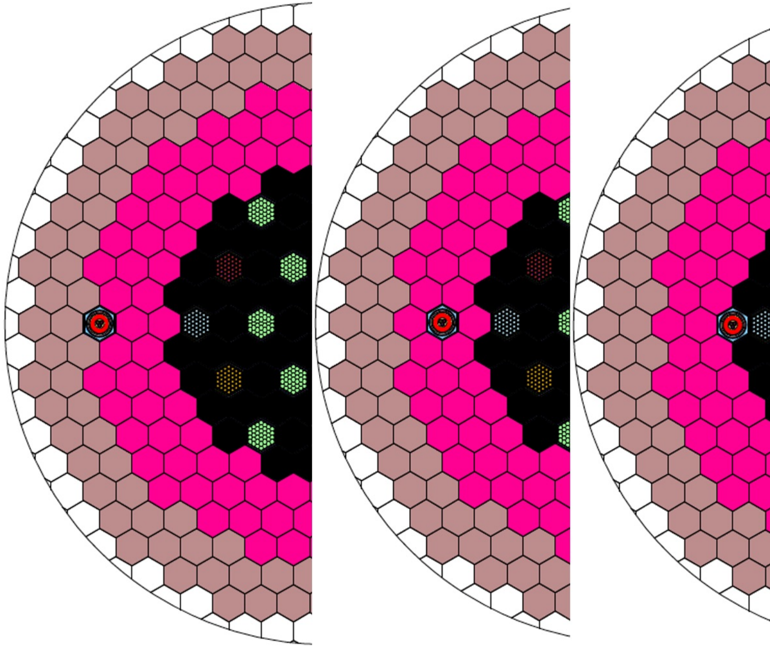




ELTA-CL Design Process – Connection with Collaborators



- Design process required frequent collaboration
  - UNM Pb corrosion tests (LOBO loop)
  - Westinghouse specifies design requirements
  - Westinghouse, LANL colleagues, and ORNL collaborate on instrumentation designs
- MCNP simulations inform
  - Westinghouse instrumentation
  - Alternate cartridge design team photon heating constraints
- Characterization of cartridge behavior at alternate locations
  - Multiple reflector locations (right)
  - Cartridge placement dependent on design objectives



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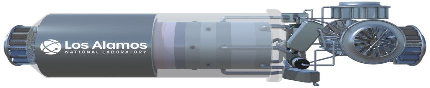
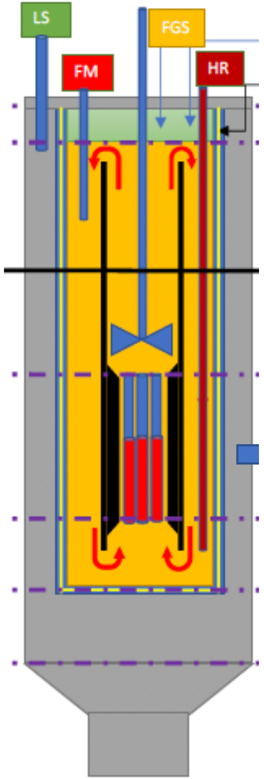
ELTA-CL Design Process – Conclusions

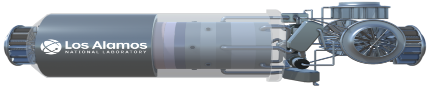


- MCNP based photon heating calculations have been invaluable
- Instrumentation design informed by neutron spectrum and flux (neutron and photon) intensities
- Non-fueled ELTA-CL design decisions have been accelerated
- Collaborations include aiding in the design of the ELTA-CG (”cartridge gas”),
  - INL & General Atomics material power depositions provided for rapid design iterations

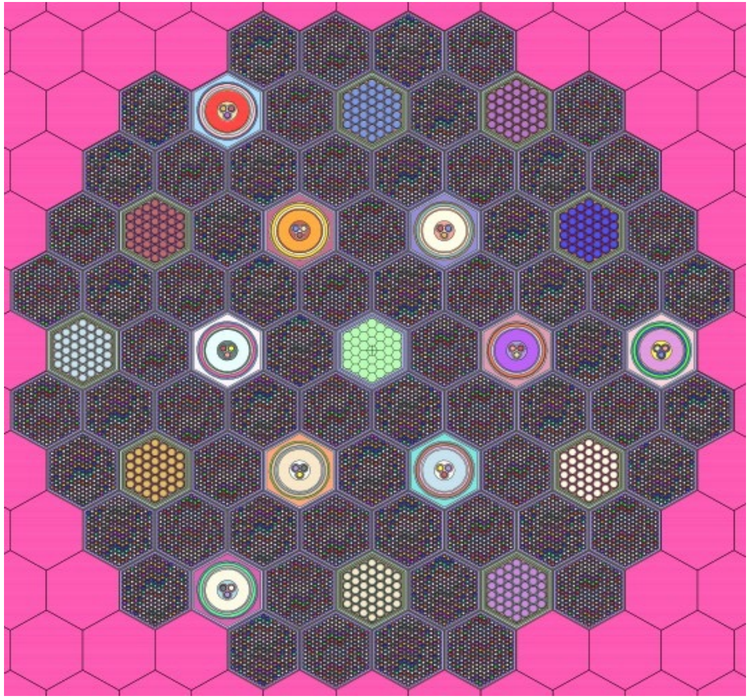


High fidelity multi-physics simulations in particle transport (MCNP), and fluid flow (CFD) have been utilized in concert to rapidly mature the ELTA-CL design, and aid collaborators across numerous institutions

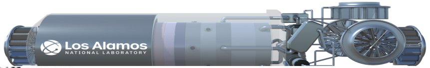
Cartridge Effects on VTR Core

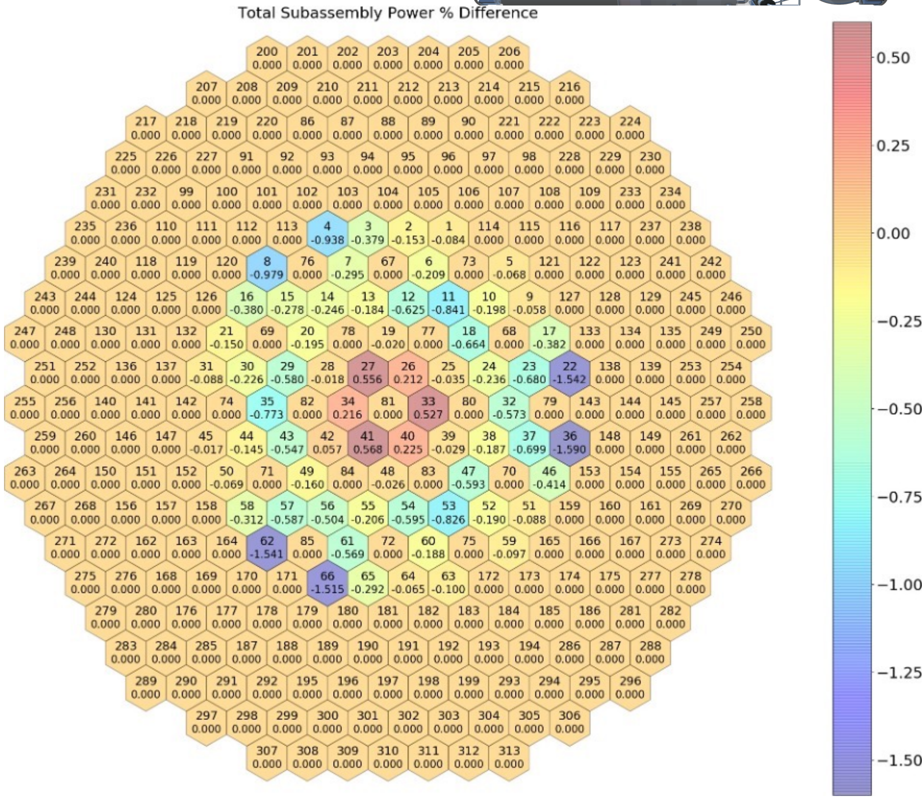


- Multiple cartridge configurations modeled
  - Individual cartridge, 9 cartridge (shown)
- Evaluate power/flux distribution differential
- Pin power peaking differential
- Effects on kinetics parameters
  - Overall reactor reactibity
  - Reactivity coefficient, control rod worths, and more…



Cartridge Effects on VTR Core





- 9 cartridge model
  - Limited impacts at the subassembly level
  - Max power increase is ~0.6%
- Power increase in center, decrease in periphery
  - Power changes in the reflector/shield are not included on the plot
- 9 cartridge reactivity impacts vary
  - -250 to +40 pcm variations
- Linear reactivity calculation
  - Single cartridge models estimate multi-cartridge loading patterns
- Fueled assemblies can provide negative reactivity compared to empty locations!